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ABSTRACT

One of the primary goals of NASA's Origins program is the search for habitable planets. I will describe how the Terrestrial Planet Finder (TPF) will revolutionize our understanding of the origin and evolution of planetary systems, and possibly even find signs of life beyond the Earth.

NASA'S TERRESTRIAL PLANET FINDER: THE SEARCH FOR (HABITABLE) PLANETS

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Scientific Goals for the Terrestrial Planet Finder

NASA's Astronomical Search for Origins is built around three main scientific goals:

- To understand how galaxies formed in the early universe and to determine the role of galaxies in the appearance of stars, planetary systems and life, e.g. what is history and evolution of the heavy elements that make life possible?
- To understand how stars and planetary systems form and to determine whether life-sustaining planets exist around other stars, e.g. where are our planetary neighbors beyond the solar system?
- To understand how life originated on Earth and to determine if it began and may still exist elsewhere as well, e.g. what are the essential and accidental properties of Earth that have made it an abode for life?

The solution to these questions will come from a number of ground-based and space-based observatories, culminating in the flight of the Terrestrial Planet Finder (TPF) which is the focus of this article.

TPF will allow us to identify habitable planets like our own Earth around the nearest stars and to assess how common they might be. By combining the sensitivity of space-borne telescopes with the high spatial resolution of an interferometer, TPF will study planets beyond our own solar system in a variety of ways: from their formation and evolution in the disks of newly forming stars to the properties of planets orbiting the nearest stars; from their numbers, sizes, locations, and diversity to their suitability as abodes for life. Using the special technique of interferometric nulling, TPF will be able to reduce the glare of parent stars by a factor of more than one hundred thousand to reveal planetary systems as far away as 15 parsec (pc) or almost 50 light years. The characterization of the size, temperature, and orbital parameters of entire planetary families, including bodies as small as the Earth in regions where liquid water might be expected to be present, i.e. the "habitable zones", will reveal the full diversity of planetary systems in a way that is only hinted at today. From this information we will be able to assess the physical and environmental effects which determine the characteristics and evolutionary fate of planets around stars of different masses and ages.

TPF will also use spectroscopy to measure the relative proportions of atmospheric gases like carbon dioxide, water, ozone, and methane to assess whether a planet someday could, or even presently does, support life. The measurement requirements for TPF have been developed and will continue to be refined through detailed discussions with atmospheric chemists and biologists, including scientists participating in NASA's newly formed Astrobiology Institute.

TPF will advance our understanding of how planets and their parent stars form. The 250 year old nebular hypothesis of Kant and Laplace holds that planets originate in a flattened disk of material resulting from the collapse of a rotating cloud of gas and dust. While this theory has been strengthened by observations of

Table 1. Illustrative TPF Configuration

Telescopes	Four (3.5 m diam)
	Diffraction-limited at 2 μm operating at <40 K
Baseline	75-1,000 m (free-flying)
Angular Resolution (maximum)	0.75 milli-arcsec(3 μm at 1,000 m baseline)
Wavelength Range	7-20 μm for planet detection; 3-30 μm for general imaging
Spectral Resolution	$R=\lambda/\Delta\lambda\sim$ 3-20 for planet detection and spectroscopy; R~3-300 for continuum and spectral line imaging
Sensitivity	0.35 μJy at 12 μm (5σ in 10^4 s at R~3)
Orbit	Earth-trailing (SIRTF) or L2
Launch Vehicle	Ariane V, EELV
Mission Duration	>5 years
Mission Launch	2012

Table 2. Observing With TPF		
Science Goal	Requirement	Observing Time
Detect Planet	Spectral Resolution =3 SNR=5	2.0 hour
Detect Atmosphere CO_2, H_2O?	Spectral Resolution=20 SNR=10	2.3 day
Is planet habitable? O_3 CH_4?	Spectral Resolution=20 SNR=25	15.1 day

protostellar disks that span tens to hundreds of astronomical units (AU) across, the recent discoveries of extra-solar planets with diverse orbital properties challenge the traditional static view that planets eternally reside at the location of their birth. As yet, we know almost nothing about the inner regions of protostellar disks where planet formation and migration is thought to occur. In the nearest star formation regions, TPF will resolve disk structures on the scale of a few tenths of an AU to investigate how gaseous and rocky planets form out of disk material. By studying the emission from dust, ices of water and carbon dioxide, and gases such as carbon monoxide and molecular hydrogen, TPF will provide essential information on the mass and temperature distribution across the protoplanetary cradle. This in turn will yield important clues on physical processes which determine the emergence, growth timescale, termination mass, ubiquity, orbital migration, and survival rates of rocky and gaseous protoplanets. The comparison of planetary systems around stars with different masses and ages will provide additional discrimination among theories of planetary orbital stability and evolution, and the probable existence of habitable planets.

Finally, TPF can investigate many other astrophysical sources where observations of milli-arcsecond structures are critical to understanding the essential physical processes. Combining the sensitivity of the Next Generation Space Telescope (NGST) with milli-arcsecond imaging, TPF will be able to study such diverse topics as the winds from dying stars that enrich the interstellar medium with heavy elements or the nature of ultra-luminous objects at high redshift that may harbor black holes, enormous bursts of star formation, or other exotic phenomena.

Illustrative Mission Concept

A variety of studies, starting with the initial suggestion of Bracewell and MacPhie (1979), have shown that an infrared *nulling* interferometer represents the best approach to the challenge of detection and spectroscopic characterization of planets around nearby stars. These concepts, and others, are reviewed in Woolf and Angel (1998) and Beichman *et al.* (1999).

The TPF configuration described in Table 1 was chosen to illuminate various technology, mission design, and cost issues and is not meant to represent a final mission design. The primary goal of planet detection and characterization will utilize core wavelengths of 7-20 μm and baselines of 50 to 200 m. Table 2 illustrates how TPF, at a representative wavelength of 12 μm, would detect and characterize an Earth orbiting a star located 10 pc away. The present TPF observatory concept can address whether a planet harbors primitive life in just two weeks of observation, roughly the time expended on the deep fields observed with the Hubble Space Telescope (Table 2).

TPF's properties can be enhanced relative to what is necessary for planet detection with only small changes to the facility. For example, broader wavelength and baseline coverage will enable high dynamic range imaging of complex astrophysical sources with the milli-arcsecond resolution previously available only with very long baseline radio interferometry. Spectral resolution of a few hundred will isolate the emission of key gases such as molecular hydrogen and carbon monoxide.

The present concept utilizes four 3.5 m diameter telescopes, each on its own spacecraft, and a central spacecraft that houses the beam combining apparatus and astronomical instrumentation. TPF will orbit in an Earth-trailing, Space Infrared Telescope Facility (SIRTF)-like, orbit or at the Earth-Sun L2 point. Other configurations involving four to six smaller telescopes are under active study by NASA and by ESA.

In the first year of its five-year mission, TPF will build on the astrometric results of the Space Interferometer Mission (SIM) to examine ~150 solitary stars within 15 pc to characterize planets discovered by SIM as well as to extend the SIM census of planets to include planets as small as the Earth. Combined SIM and TPF data will allow a very detailed physical characterization of planets ranging in mass from Jupiter to a few times the Earth mass. In subsequent years, TPF will carry out a program of spectroscopic follow-up of the most promising targets to search for habitable or inhabited planets, as well as in mapping a broad range of astrophysical targets.

Technology

While TPF presents many challenges, the key technologies are being addressed by a variety of NASA programs in preparation for launch of TPF at the end of the next decade. At the beginning of TPF's development phase around 2007, the missions listed below will have demonstrated almost all of the key technologies needed for TPF. A few TPF-specific technologies will have to be developed in a carefully planned technology program.

- NGST will fly a cooled, 8-m light-weight mirror (~10-15 kg m^{-2}) with cryogenic actuators and precision wavelength control. Smaller mirrors utilizing the same technology will be used by TPF.
- Ground-based interferometers such as the Keck Interferometer, the Large Binocular Telescope, and European Southern Observatories (ESO's) Very Large Telescope Interferometer (VLTI) will develop hardware techniques, software packages, and a community that is ready to use TPF.
- The Space Interferometer Mission (SIM) will be a fully functional space-borne interferometer that will demonstrate all aspects of interferometry including star-light nulling. SIM will demonstrate the pathlength control needed for TPF.
- The Space Technology-3 mission will demonstrate precision formation flight and nanometer pathlength control with two spacecraft separated by up to a 1 km distance to form a visible light interferometer.
- Laboratory investigations have already begun to address the demanding requirements for deep interferometric nulling. Stable, broadband (18%), nulls as deep as one part in 14,000 in visible light have already been achieved in the laboratory.

Programmatic Considerations

The Origins program consists of a progression of technology development activities, technology demonstrations, and science missions that produce important scientific results and new capabilities at each step in the program. Within the context of this overall program, TPF is presently being considered by NASA for a new start in 2007 after the successful completion of key technological milestones during the development of the Space Interferometer Mission (SIM) and the Next Generation Space Telescope (NGST). TPF could be launched as early as 2012. The European Space Agency is presently studying the Infrared Space Interferometer (IRSI, formerly known as Darwin) for possible inclusion as a cornerstone mission in its Horizon 2000+ program. IRSI shares many of the scientific goals and technological challenges of TPF. Astronomers and engineers from both projects have established the groundwork for a fruitful collaboration on a project of broad public interest. Beichman, Woolf, and Lindensmith (1999) describe the TPF mission in more detail. Additional information on the Terrestrial Planet Finder can also be found on the TPF web site at http://tpf.jpl.nasa.gov.

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